

Charmonium suppression in p-A collisions at RHIC

François Arleo, Pol-Bernard Gossiaux, and Jörg Aichelin

SUBATECH

*Laboratoire de Physique Subatomique et des Technologies Associées
UMR Université de Nantes, IN2P3/CNRS, Ecole des Mines de Nantes*

4, rue Alfred Kastler, F-44070 Nantes Cedex 03, France.

We discuss charmonium production in proton-nucleus collisions at RHIC energies under the assumption of x_F and x_2 scaling. We find that all the ambiguities due to energy loss are gone at this energy and therefore data will reveal the scaling law, if any. These p-A data will also be crucial to interpret nucleus-nucleus data with respect to a possible formation of a quark gluon plasma because the extrapolations for charmonium production from the present p-A data to RHIC energies, based on the two scaling laws, differ by a factor of four.

I. SCALING IN CHARMONIUM NUCLEAR PRODUCTION

Charmonium production off nuclei has shown to be strongly affected by nuclear effects in proton induced reactions at several beam energies [1–4]. It is therefore natural to wonder whether the nuclear dependence of charmonium production is actually driven by a scaling variable, independently of the center-of-mass energy \sqrt{s} of the collision. Indeed, a first glimpse at proton-nucleus data at SPS [1] and Fermilab [3,4] tends to indicate that J/ψ suppression scales with the longitudinal momentum fraction Feynman- x (x_F).

Such an x_F scaling has been predicted long ago within the intrinsic charm model [5]. Indeed, charmonium production at large x_F may be dominated by the soft scattering of the intrinsic $c\bar{c}$ component of the projectile on the front surface of the nucleus leading to an unusual $A^{2/3}$ dependence at high x_F , i.e., a suppression as compared to the A^1 dependence of the hard parton fusion process. However, the intrinsic charm content of the proton required to describe quantitatively the data is somewhat larger than what is found from a leading order analysis of the EMC charm structure functions [6].

Furthermore, it is expected from the QCD factorization theorem that nuclear effects at high energy scale with the momentum fraction x_2 carried by the target parton from the nucleus. Furthermore, absorption of charmonia in nuclear matter depends on the space-time evolution of the expanding $c\bar{c}$ state [7] as well as on the energy dependence of the charmonium hadron inelastic cross sections [8]. Since both the Lorentz factor γ of the $c\bar{c}$ system in the nucleus rest frame (i.e., which governs the expansion of the $c\bar{c}$ precursor in the nucleus) and the incident energy $\sqrt{s_{\psi h}}$ are related to the momentum fraction x_2 , final state interactions naturally lead to an x_2 scaling in charmonium suppression, assuming a given

mass for the $c\bar{c}$ state. Similarly, the effects of nuclear shadowing [9] in charmonium production are expected to depend on x_2 , independently of the center-of-mass energy of the collision. However, we would like to point out that possible effects of parton energy loss in nuclear matter might distort a possible x_2 scaling law at low beam energy [10,11].

On the experimental side, we emphasized that the comparison of NA3 [1] ($\sqrt{s} = 19.4$ GeV) and E772 [3] ($\sqrt{s} = 38.8$ GeV) data seems to show that J/ψ suppression in proton-nucleus collisions scales with the longitudinal momentum fraction Feynman- x (x_F) [3]. However, x_F scaling is no longer reported in pion-nucleus NA3 data [1] from $\sqrt{s} = 16.7$ GeV to $\sqrt{s} = 22.3$ GeV [12]. The x_2 scaling assumption appears to be ruled out at small $x_2 \approx 0.07$ when considering NA3 and E866/NuSea p-A data, even though a good agreement is found at larger x_2 . Thus, it is our understanding that two quite different scenarios can be invoked in order to explain the present p-A data : i) A universal x_F scaling law, valid from $\sqrt{s} \approx 20$ GeV on; ii) A x_2 scaling law visible at higher energy, but distorted in the low energy range by effects such as energy loss. Unfortunately, no clear and definitive conclusion can be drawn from the present experimental results, first of all because considerable error bars weaken the confidence one could have in some of the most relevant data points, but also because energy loss effect is in fact not perfectly understood at NA3 energies.

In order to distinguish clearly which scaling law, if any, governs nuclear effects seen in charmonium production, one thus has to turn to higher \sqrt{s} , such as presently available at the RHIC accelerator. It is the main goal of this article to show that energy loss effects are indeed negligible in this energy range, while x_2 and x_F scaling law assumptions lead to quite different predictions for the production rate of charmonium in proton-nucleus collisions planned in year III of RHIC. Consequences for the

interpretation of nucleus-nucleus experiment are eventually investigated.

II. RHIC PREDICTIONS

Using the 800 GeV proton beam at Fermilab, the fixed target experiment E866/NuSea measured J/ψ and ψ' production off several nuclear targets (Be, Fe, and W) over a wide kinematical range [4]. The production ratio

$$R(W/Be, x_F) = \frac{9 d\sigma(pW \rightarrow \psi(x_F)X)}{184 d\sigma(pBe \rightarrow \psi(x_F)X)},$$

has been extracted for longitudinal momentum fractions $-0.1 \leq x_F \leq 0.93$. It is found to decrease strongly from $R(W/Be)=0.86$ at $x_F \approx 0.2$ down to $R(W/Be)=0.3$ at $x_F = 0.9$.

In [4], the x_F dependence of the differential production ratio has shown to be consistent with

$$R(W/Be, x_F) = \left(\frac{184}{9}\right)^{\alpha(x_F)-1}$$

where $\alpha(x_F)$ follows the fitting law

$$\alpha^{E866}(x_F) = 0.960 (1 - 0.0519 x_F - 0.338 x_F^2)$$

in the whole experimental x_F range.

x_F scaling. Assuming x_F to be the proper scaling variable, i.e., R independent of \sqrt{s} , the expected J/ψ production rate at RHIC is straightforward. Provided the power law $\sigma(A) \propto A^\alpha$ is valid even for light systems, the ratio $R(Au/p, x_F)$ in p(100 GeV)+A(100 AGeV) is simply given by

$$R(Au/p, x_F) = 197^{\alpha^{E866}(x_F)-1}.$$

The simple relation between x_F and the J/ψ rapidity

$$y^{J/\psi} = \text{Arcsinh} \left(\frac{x_F \sqrt{s}}{2 m_{J/\psi}} \right),$$

determines the rapidity range over which reliable RHIC predictions, based on E866 data, can be made. This range is summarized in Table I. The corresponding production ratio is displayed in Figure 1 (*solid*) as a function of $y_{cm}^{J/\psi}$. Provided x_F scaling, charmonium suppression is expected to be small ($R \approx 0.8$) and approximately constant in the range $-2 \leq y_{cm}^{J/\psi} \leq 2$. The large nuclear effects seen in E866 data are found to be relevant at RHIC for rapidities greater than $y_{cm}^{J/\psi} \approx 2.6$ (cf. Table I, *right* and Figure 1).

x_2 Scaling. The scaling with the momentum fraction x_2 leads to a significantly different suppression pattern. Expressing x_2 as a function of x_F

$$x_2^{J/\psi} = \frac{1}{2} \left(-x_F + \sqrt{x_F^2 + 4m_{J/\psi}^2/s} \right)$$

	full range	steep drop
x_F in E866	$-0.1 \leq x_F \leq 0.93$	$0.2 \leq x_F \leq 0.93$
$y_{cm}^{J/\psi}$ at RHIC	$-1.9 \leq y_{cm}^{J/\psi} \leq 4.1$	$2.6 \leq y_{cm}^{J/\psi} \leq 4.1$

TABLE I. x_F range covered by the E866/NuSea data and the corresponding J/ψ rapidity range at RHIC ($\sqrt{s} = 200$ AGeV) (*left*). Ranges for which the ratio $R(W/Be)$ sharply drops are also given (*right*).

and the J/ψ rapidity as a function of x_2

$$y_{cm}^{J/\psi} = \ln \left(\frac{m_{J/\psi}}{x_2^{J/\psi} \sqrt{s}} \right),$$

the sudden drop of the production ratio R occurs around midrapidity at RHIC energies, as shown in Table II (*right*). Furthermore, we note that x_2 scaling predictions, based on E866 data, are limited to the rapidity range $-1.1 \leq y_{cm}^{J/\psi} \leq 0.8$ (Table II, *left*).

	full range	steep drop
x_2 in E866	$0.044 \geq x_2 \geq 0.006$	$0.028 \geq x_2 \geq 0.006$
$y_{cm}^{J/\psi}$ at RHIC	$-1.1 \leq y_{cm}^{J/\psi} \leq 0.8$	$-0.6 \leq y_{cm}^{J/\psi} \leq 0.8$

TABLE II. x_2 range covered by the E866/NuSea data and the corresponding J/ψ rapidity range at RHIC ($\sqrt{s} = 200$ AGeV) (*left*). Ranges for which the ratio $R(W/Be)$ sharply drops are also given (*right*).

Thus, the steep fall of charmonium production seen in E866 data appears in two distinct rapidity ranges at RHIC, depending on whether it scales with x_F or x_2 . Consequently, the rapidity dependence of charmonium production measured in proton-nucleus collisions at RHIC may allow one to disentangle these two assumptions.

The Model. The expected charmonium rate at RHIC under the x_2 scaling assumption is discussed in this section. In order to extrapolate to x_2 ranges not covered by E866 data (Table II), we use a recently advanced x_2 scaling model based on absorption mechanisms [13]. Here, it will be complemented by a calculation of parton energy loss, that has been proven to be relevant at low beam energy [10].

The model is based on a standard two stage color neutralization scenario. A compact partonic $(c\bar{c})_8$ state is assumed to be produced by parton fusion in a color octet

state. The latter will then turn into a singlet $(c\bar{c})_1$ state after a color neutralization time $\tau_{8 \rightarrow 1}$. During the first stage, the octet state may interact with surrounding nucleons with an octet cross section $\sigma_{(c\bar{c})_8 N}$, taken to be independent of its transverse size $r_{c\bar{c}}$. Adopting an energy dependence related to J/ψ photoproduction data, the octet nucleon cross section reads as

$$\sigma_{(c\bar{c})_8 N} = \sigma_8 \cdot \left(\frac{\sqrt{s}}{10 \text{ GeV}} \right)^{0.4}.$$

The singlet-nucleon total cross section $\sigma_{(c\bar{c})_1 N}$ is proportional to the square of the radius $r_{c\bar{c}}$ and has a same energy dependence. We assume that the transverse distance between the quarks increases linearly with time until the respective hadronic radius r_i is reached. In the $c\bar{c}$ rest frame, we write

$$r_{c\bar{c}}(\tau) = \begin{cases} r_0 + v_{c\bar{c}} \tau & \text{if } r_{c\bar{c}}(\tau) \leq r_i, \\ r_i & \text{otherwise,} \end{cases}$$

where i stands for J/ψ , ψ' and χ . Therefore, the time dependent cross sections for singlet states are given by

$$\sigma_{(c\bar{c})_1 N}(\tau) = \sigma_1 \cdot \left(\frac{\sqrt{s}}{10 \text{ GeV}} \right)^{0.4} \left(\frac{r_{c\bar{c}}(\tau)}{r_\psi} \right)^2.$$

Using one common set of parameters fitted to E866/NuSea results¹, almost all other available data on charmonium production in p-A collisions can be reproduced within this approach [13].

As this inelastic cross section is intimately related to the time evolution of the $c\bar{c}$ system that travels through the nucleus, charmonium absorption within this model is driven by the Lorentz boost γ of the $c\bar{c}$ pair in the nucleus rest frame:

$$\gamma = \frac{m_{c\bar{c}}}{2x_2 m_p},$$

where x_2 is the momentum fraction carried by the target parton and $m_{c\bar{c}} \approx m_{J/\psi}$. It therefore leads to x_2 scaling for the nuclear charmonium absorption.

Let us now turn to the predictions of the model. Using the same set of parameters, we have calculated charmonium suppression in p(100 GeV)+A(100 AGeV) collisions over a wide range of rapidities ($-3 \leq y_{cm} \leq 3$). The J/ψ (dashed) and ψ' (dotted) production ratios $R(\text{Au}/p)$ are depicted in Figure 1. As expected, both ratios dramatically drop around mid-rapidity. In our model, this fall is a consequence of the increase of color-octet nucleon inelastic interactions (as compared to the color-singlet nucleon interactions) with γ , *i.e.* with x_F . Nevertheless, we would like to remind the reader that such a qualitative

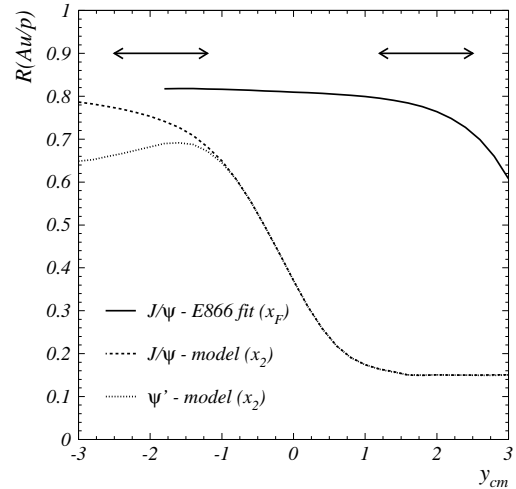


FIG. 1. Ratio $R(\text{Au}/p)$ versus y_{cm} of produced J/ψ 's within the E866/NuSea fit (solid line) in p(100 GeV)+Au(100 GeV) collisions, assuming x_F scaling. The model prediction for J/ψ (dashed) and ψ' (dotted) production ratio is also shown. The arrows show the dimuon arm acceptance in the PHENIX experiment.

feature can also be seen as a direct consequence of the x_2 scaling assumption, together with the particular x_2 dependence of the E866/NuSea data. Actual predictions of the model are in fact the behavior for the rapidity ranges $y_{cm} < -1$ and $y_{cm} > 1$.

At large y_{cm} (*i.e.*, large γ factor), the partonic $c\bar{c}$ state travels through the entire nucleus in a color octet state and hence leads to a constant $R(\text{Au}/p)^2$ as low as $R \approx 0.2$.

The smaller the values of y_{cm} the more likely the color neutralization to happen inside the nucleus. For negative y_{cm} the charmonia have time to expand to their asymptotic size inside the nucleus. Then, J/ψ and ψ' 's have different cross sections with the surrounding matter and consequently the respective production ratios differ (Fig. 1). Finally, let us also mention that these general trends are found to be similar in lighter systems.

III. SHADOWING AND ENERGY LOSS

So far, charmonium suppression has been attributed to the inelastic interactions of the $c\bar{c}$ pair in nuclear matter. Let us investigate in this section the effects of both shadowing and parton energy loss in the nuclear dependence of charmonium suppression at RHIC energies.

¹ $r_0 = 0.15$ fm, $v_{c\bar{c}} = 1.85$, $\sigma_1 = 2.1$ mb, $\tau_{8 \rightarrow 1} = 0.02$ fm, $\sigma_8 = 22.3$ mb.

²Actually a slight decrease is expected due to the weak energy dependence of the octet-nucleon cross section (see section II.A)

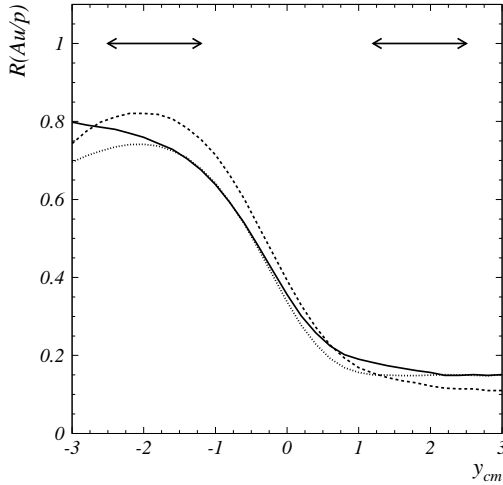


FIG. 2. Ratio $R(\text{Au}/p)$ versus y_{cm} of produced J/ψ 's in $p(100 \text{ GeV}) + \text{Au}(100 \text{ AGeV})$ collisions predicted by the model assuming nuclear absorption only (solid), nuclear absorption with EKS98 shadowing (dashed), nuclear absorption with BDMPS energy loss (dotted).

Shadowing. It is known from the first EMC data that structure functions $F_2^A(x)$ in a heavy nucleus strongly differ from that measured in light targets. At small $x_2 \ll 1$ (i.e., large $y_{\text{cm}}^{J/\psi}$), the depletion of parton distributions (*shadowing*) lowers the charmonium nuclear production, hence leading to a production ratio smaller than one. On the contrary, possible gluon anti-shadowing between $0.1 < x_2 < 0.3$ enhances charmonium production in a nucleus in the range $-3 < y_{\text{cm}}^{J/\psi} < -1.8$ at $\sqrt{s} = 200 \text{ GeV}$.

Shadowing effects on J/ψ suppression in proton-nucleus collisions have been investigated by several authors [9]. They all report that it leads to a J/ψ suppression at large x_F at Fermilab energy in agreement with the general trend reported by E772 [3] and E866/NuSea [4].

We compute in Figure 2 (dashed) the J/ψ production ratio in $p(100 \text{ GeV})\text{-Au}(100 \text{ AGeV})$ assuming both nuclear absorption and shadowing effects. The production cross sections are given by the color evaporation model with MRST parton distributions [14]. Nuclear shadowing is evaluated using the parameterization of deep inelastic scattering and Drell-Yan data by Eskola *et al.* (EKS98) [15]. A glimpse at Figure 2 indicates that the general trend predicted for the rapidity dependence of J/ψ suppression still holds when shadowing of target partons is taken into account. We also note that measurements in the negative rapidity range ($-2.2 < y_{\text{cm}}^{J/\psi} < -1.1$) may signal gluon antishadowing effects. Furthermore, charmonium production at large rapidities ($y_{\text{cm}}^{J/\psi} \leq 2$) will reveal a possible saturation of shadowing at small $x_2 \sim 10^{-3}$.

While the EKS98 shadowing based on the factorization of the nuclear structure functions leads only to a *small* suppression as compared to nuclear absorption, it is worth pointing out that a rapidity dependence for

J/ψ suppression at RHIC similar to the one in Figure 2 has also been predicted as coming from coherence effects *only* [16].

Energy loss. The incoming parton from the projectile may suffer multiple scatterings while traveling through the nucleus A , hence leading to a shift of its momentum fraction from $x_1 + \Delta x_1$ to x_1 at the time of the $c\bar{c}$ production. In addition to final state interactions, ψ production in a nucleus will thus be suppressed roughly by a factor

$$\sigma(pp \rightarrow \psi(x_1 + \Delta x_1)X) / \sigma(pp \rightarrow \psi(x_1)X) \quad (1)$$

Because of the dramatic drop of the parton distributions at large x (especially that of the gluon), one may reasonably expect a significant suppression even for small shifts of the momentum fraction x_1 .

A lot of theoretical effort has been devoted in the last few years to relate the momentum fraction shift Δx_1 to the atomic mass number A and the center-of-mass energy \sqrt{s} of the collision [17–19]. For the numerical computations to follow, we shall adopt the model by Baier *et al.* (BDMPS) [19] which assumes the radiative energy loss per unit length $\Delta E/\Delta z$ to depend linearly on the length $z \propto A^{1/3}$ covered by the parton in the nucleus, i.e.,

$$\frac{\Delta E}{\Delta z} \propto A^{1/3}$$

which leads to a momentum fraction shift

$$\Delta x_1 = \frac{\kappa}{s} A^{2/3} \quad (2)$$

where κ is a free parameter³. While the momentum fraction shift (2) vanishes at large energy \sqrt{s} , energy loss effects on charmonium production are expected to be sizeable at low incident energies when Δx_1 becomes large. We already emphasized that such a mechanism may thus be responsible for the lack of x_2 scaling seen from NA3 to Fermilab data in J/ψ production [10,11].

Let us now estimate more quantitatively the effects of energy loss in J/ψ production at RHIC energy. We apply the BDMPS model [19] with a quark energy loss $\Delta E/\Delta z = 0.3 \text{ GeV/fm}$ ($\kappa = 0.086 \text{ GeV}^2$) in a gold nucleus⁴. Energy loss of this magnitude together with the absorption model appears to be consistent with both NA3 and E866/NuSea J/ψ data [11]. Again, the production cross sections in (1) are computed within the color evaporation model and using MRST parton distributions [14].

The J/ψ production ratio $R(\text{Au}/p)$ in $p(100 \text{ GeV}) + \text{Au}(100 \text{ AGeV})$ collisions including energy loss is

³We assume that the perturbative analysis of BDMPS is justified at the energies of RHIC. This may no longer be true at SPS energy where the incoming parton energy is small.

⁴The corresponding gluon energy loss is expected to be $dE/dz|_g = 9/4 dE/dz|_q \approx 0.7 \text{ GeV/fm}$ in a gold nucleus.

displayed in Figure 2 (*dotted*). Energy loss proves to be relevant in the nucleus fragmentation region and to be negligible otherwise. Therefore, the large suppression predicted at RHIC by the x_2 scaling assumption is not altered by such a mechanism. We further note that possible energy loss effects may be seen and better understood [11] at HERA-B where charmonium and Drell-Yan production will be measured in p(920 GeV)-nucleus collisions for $-0.5 \leq x_F \leq 0.3$ [20].

Whereas we focus here on hadron-nucleus reactions, we would like to emphasize that parton energy loss in hot QCD matter (or “jet quenching”, [21]) is expected to be even much larger than that in nuclei of about one order of magnitude [19,21]. We note that the PHENIX collaboration at RHIC recently reported on the suppression of the yield of high p_T hadrons that may be attributed to finite parton energy loss [22]. In view of that, determination of finite energy loss in proton-nucleus collisions would certainly help to constrain estimates obtained in nucleus-nucleus collisions. Finally, let us also mention that elastic scatterings of the produced $c\bar{c}$ pair with the nucleus (*final state* energy loss) may also lead to large effects in the nuclear dependence of J/ψ production [23], although the radiative energy loss of heavy quarks may be much smaller than the one of light quarks [24].

Furthermore, we have checked that this particular rapidity dependence is expected to persist when nuclear shadowing of target partons, predicted by the EKS98 parameterization [15], is taken into account.

IV. EXPERIMENTAL CONSIDERATIONS

The results presented so far show that charmonium production in p-A collisions at RHIC energies will allow to *discard* experimentally one of the two presently advanced scaling assumptions in charmonium production. For ruling out one of the assumptions it is indeed sufficient to measure charmonium production in the rapidity interval $1 < y_{cm} < 2$. Such a measurement can be carried out by the present setup of the PHENIX experiment which is sensitive to charmonium production in the dimuon decay channel for the rapidity range $1.2 \leq |y_{lab}| \leq 2.4$, represented by black arrows in Figure 1.

However, if one would like to *confirm* scaling, either in x_F or x_2 , a precise measurement in the region where R drops sharply is necessary, i.e. either in the rapidity range $2.6 \leq y_{cm}^{J/\psi} \leq 4.1$ or in $-0.6 \leq y_{cm}^{J/\psi} \leq 0.8$ respectively (see Tables I and II, *right*). These domains are most unfortunately not covered by the dimuon spectrometer acceptance, although the midrapidity region could be explored via the e^+e^- decay channel of J/ψ .

As for the backward dimuon spectrometer, it will permit to investigate formation time effects in charmonium production, as demonstrated in Figure 1. In particular, the ψ' over J/ψ ratio in various nuclei in this rapidity

range may allow to constrain formation times estimates as well as the time evolution of the partonic system. Both are not precisely known so far.

One may wonder whether energy asymmetric collisions like p(250 GeV)+A(100 AGeV) [25] allow to investigate scaling with the present detector acceptance. As shown in Figure 3 this is not very promising. In order to observe the steep drop of R in the acceptance region, one has in fact to lower the gold beam energy even further, e.g., p(250 GeV)+Au(65 AGeV).

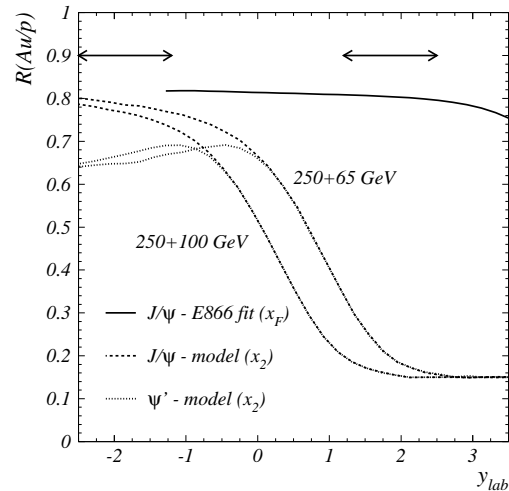


FIG. 3. Idem as Figure 1 in asymmetric p(250 GeV)+Au(100 AGeV) and p(250 GeV)+Au(65 AGeV) collisions.

V. BASELINE TO NUCLEUS-NUCLEUS DATA

Heavy quarkonium suppression is expected to signal a quark-gluon plasma (QGP) formation in nucleus-nucleus collisions [26]. On the contrary, no deconfinement is expected in proton-nucleus collisions. Therefore, p-A measurements provide a natural benchmark to which a possible additional suppression due to QGP formation has to be compared with.

However, we have seen that the expected J/ψ rate in proton-nucleus collisions is strongly dependent on the scaling law of the underlying mechanism responsible for charmonium suppression. To illustrate this, let us give an estimate for J/ψ production ratio in inclusive Au-Au collisions at $\sqrt{s} = 200$ AGeV, assuming no abnormal suppression (i.e. no QGP formation). In this case, the production ratio at a given y_{cm} is expected to be roughly

$$R(\text{Au} - \text{Au}, y_{cm}) \approx R(\text{Au} - \text{p}, y_{cm}) R(\text{Au} - \text{p}, -y_{cm})$$

Assuming x_F scaling, we expect a constant production ratio $R(\text{Au}/\text{p}) \approx 0.64$ in $y_{cm} \in [-2, 2]$. Provided x_2 scaling prevails in charmonium nuclear production, this ratio is also constant and as low as $R(\text{Au}/\text{p}) \approx 0.16$.

Thus, the extrapolation from presently available p-A data to the hadronic suppression expected at RHIC energies yields an uncertainty of a factor of four. Therefore, an unambiguous judgement whether J/ψ suppression seen in A-A collisions at RHIC is due to QGP formation has to await for p-A measurements at the same energy over a wide range of rapidities.

-
- [1] J. Badier *et al.* (NA3), Z. Phys. C **20**, 101 (1983).
 - [2] M. C. Abreu *et al.* (NA38), Phys. Lett. B **449**, 128 (1999).
 - [3] D. M. Alde *et al.* (E772), Phys. Rev. Lett. **66**, 133 (1991).
 - [4] M. J. Leitch *et al.* (FNAL E866/NuSea), Phys. Rev. Lett. **84**, 3256 (2000).
 - [5] S. J. Brodsky and P. Hoyer, Phys. Rev. Lett. **63**, 1566 (1989).
 - [6] E. Hoffmann and R. Moore, Z. Phys. C **20**, 71 (1983).
 - [7] J.-P. Blaizot and J.-Y. Ollitrault, Phys. Lett. B **217**, 386 (1989); G. R. Farrar, H. Liu, L. L. Frankfurt, and M. I. Strikman, Phys. Rev. Lett. **61**, 686 (1988); R. Vogt, S. J. Brodsky, and P. Hoyer, Nucl. Phys. **B360**, 67 (1991); L. Gerland, L. Frankfurt, M. Strikman, H. Stöcker, and W. Greiner, Phys. Rev. Lett. **81**, 762 (1998); F. Arleo, P.-B. Gossiaux, T. Gousset, and J. Aichelin, Phys. Rev. **C61**, 054906 (2000).
 - [8] K. Martins, D. Blaschke, and E. Quack, Phys. Rev. **C51**, 2723 (1995); S. G. Matinyan and B. Müller, Phys. Rev. **C58**, 2994 (1998); C.-Y. Wong, E. S. Swanson, and T. E. Barnes, Phys. Rev. **C62**, 045201 (2000); F. Arleo, P.-B. Gossiaux, T. Gousset, and J. Aichelin, hep-ph/0102095, to appear in Phys. Rev. D.
 - [9] R. Vogt, S. J. Brodsky, and P. Hoyer, Nucl. Phys. **B360**, 67 (1991); C. Pajares, C. A. Salgado, and Yu. M. Shabelski, Mod. Phys. Lett. **A13**, 453 (1998); R. Hwa, J. Piśút, and N. Piśútová, Phys. Rev. Lett. **85**, 4008 (2000); B. Z. Kopeliovich, A. Tarasov, and J. Hüfner, preprint hep-ph/0104256 (2001).
 - [10] F. Arleo, P.-B. Gossiaux, T. Gousset and J. Aichelin, hep-ph/0005230 (2000).
 - [11] F. Arleo, Ph.D. thesis (2001).
 - [12] S. Gupta and H. Satz, Z. Phys. C **55**, 391 (1992).
 - [13] F. Arleo, P.-B. Gossiaux, T. Gousset, and J. Aichelin, Phys. Rev. **C61**, 054906 (2000).
 - [14] A. D. Martin, R. G. Roberts, W. J. Stirling, and R.S. Thorne, Eur. Phys. J. **C4**, 463 (1998).
 - [15] K. Eskola, V. Kolhinen and C. Salgado, Eur. Phys. J. **C9**, 61 (1999).
 - [16] B. Z. Kopeliovich, A. Tarasov, and J. Hüfner, preprint hep-ph/0104256 (2001).
 - [17] S. Gavin and J. Milana, Phys. Rev. Lett. **68**, 1834 (1992).
 - [18] S. J. Brodsky and P. Hoyer, Phys. Lett. B **298**, 165 (1993).
 - [19] R. Baier, Yu. L. Dokshitzer, A. H. Mueller, S. Peigné, and D. Schiff, Nucl. Phys. **B484**, 265 (1997).
 - [20] M. Bruinsma *et al.* (HERA-B), poster at Quark Matter 2001, Stony Brook, Jan. 15-20 2001.
 - [21] R. Baier, Yu. L. Dokshitzer, A. H. Mueller, S. Peigné, and D. Schiff, Nucl. Phys. **B483**, 291 (1997); M. Gyulassy and X.-N. Wang, Nucl. Phys. **B420**, 583 (1994); X.-N. Wang, Phys. Rev. **C58**, 2321 (1998); M. Gyulassy, P. Levai, and I. Vitev, Phys. Rev. Lett. **85**, 5535 (2000).
 - [22] K. Adcox, *et al.*, preprint hep-ex/0109003 (2001).
 - [23] D. Kharzeev and H. Satz, Z. Phys. C **60**, 389 (1993). R. Vogt, Phys. Rev. **C61**, 035203 (2000).
 - [24] Yu. L. Dokshitzer and D. E. Kharzeev, preprint hep-ph/0106202 (2001).
 - [25] “White paper on proton-nucleus collisions”, Town Meeting on p-A physics at RHIC, Brookhaven, Oct. 27-29 2000.
 - [26] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).